Comparison of Dam Breach Parameter Estimators

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ABSTRACT

Analytical techniques for the estimation of dam breach parameters were evaluated and compared. The development of potential flooding from a dam failure requires several elements; the hydrologic scenario, the possible dam failure modes, breach parameters that are associated with the failure modes, and the routing and mapping of the consequent discharge hydrograph. This paper presents recent research into the use and application of several dam breach parameter estimators to describe the physical characteristics of a dam breach, use of those parameters within the unsteady flow routing model HEC-RAS, and the computation and display of the resulting downstream impacts. The breach parameter estimators that were used include both empirical and embankment erosion process models.

INTRODUCTION

Many agencies are reviewing and updating dam safety and risk studies. The Corps of Engineers is performing a portfolio risk analysis of their projects. Included in that study is the updating of probable maximum flood inflow hydrographs and routing of potential dam break floods to ascertain downstream consequences. The estimation of possible breach dimensions and development times is necessary in any assessment of dam safety. The breach parameters will directly and substantially affect the estimate of the flows, inundated areas and warning times at downstream locations. The breach location, size, and formation time are often the most uncertain pieces of information in a dam failure analysis. Application of several commonly used analysis techniques to several projects is described in this paper.

The geometric description of a dam breach must be estimated to simulate the resultant flood wave and downstream consequences. Some readily available models that can be used for performing dam breach outflow hydrograph computation and downstream routing are HEC-RAS (HEC, 2006a), HEC-HMS (HEC, 2006b), NWS-DAMBRK (Fread, 1988b), NWS-FLDWAV (Fread, 2000), and a few others. These models require that the potential breach characteristics be estimated outside of the model. Several "process" models are also available, or being developed, that attempt to simulate the progression of a dam breach using sediment transport equations to estimate erosion rates and soil mechanics relations to predict mass slope failures. One process model that is discussed herein is the NWS-BREACH model (Fread, 1988a).

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Breach dimensions and time of development must be estimated for various failure scenarios. This requirement includes different failure modes as well as different hydrologic events. The breach parameters associated with a hydrologic event of the scale of the probable maximum flood may differ from those for a sunny day failure triggered, perhaps, by a seismic event. Therefore, a set of breach parameters needs to be developed for each combination of antecedent pool elevation (hydrologic event) and failure scenario.

The breach characteristics can be estimated in several ways; including: comparative analysis (comparing the study project to historical failures of dams of similar size, materials, and water volume); regression equations (equations developed from historical dam failures in order to predict peak outflow or breach size and development time); and physically based computer models (computer programs that attempt to model the physical breaching process by using sediment transport/erosion equations, soil mechanics, and principles of hydraulics). All of these methods are viable techniques for estimating breach characteristics.

Reasonable values for the breach size and development time are needed to make a reliable estimate of the outflow hydrographs and resulting downstream inundation, flood travel times, water velocities, etc. These parameters describing the breach have large uncertainty. The HEC-RAS and HEC-HMS software require the following information to describe a dam breach:

Failure Location

The breach failure location depends on many factors, such as; type and shape of dam, failure mode, and structural elements of the dam. All factors concerning the dam, particularly any historical records of seepage and foundation problems, should be considered in order to place the breach in the most probable location for each failure mode. If a most probable location cannot be identified, then the centerline of the breach should be set to the centerline of the downstream main channel

Failure Mode

The hydraulic algorithms in HEC-RAS and HEC-HMS are designed to simulate the hydraulics of overtopping and piping failures. The failure mode is the mechanism for starting and growing the breach. Overtopping failures start at the top of the dam and grow to maximum extents, while a piping failure can start at any elevation/location and grow to the maximum extents. The ultimate breach size and breach development time are much more critical in the estimation of the outflow hydrograph than the actual failure mode.

Breach Development Time

Both HEC-RAS and HEC-HMS require as input data a breach development time. That time is described as follows:

Overtopping Failure: The time, from when the breach has eroded back to the upstream side of the top of the dam, to when the breach is fully formed (ie., significant erosion has stopped, not the time until the reservoir pool is emptied).

Piping Failure: The time from when a significant amount of flow and material are moving through the piping failure to when the breach is fully formed
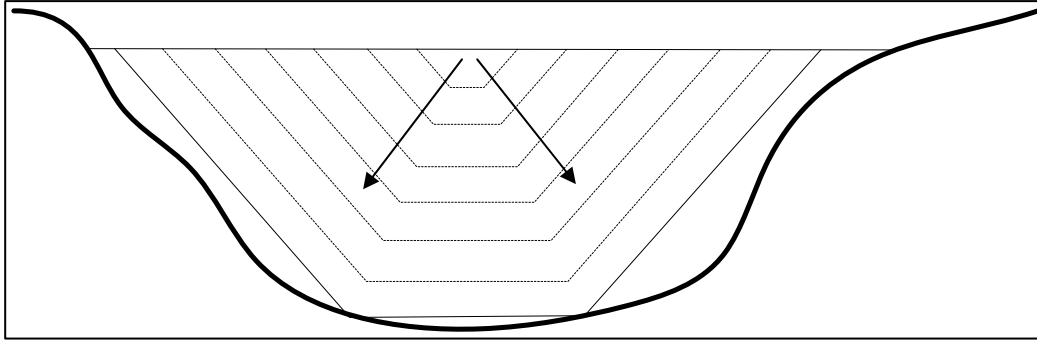
Figure 1. Generalized Trapezoidal Breach Progression

(significant erosion has stopped, not the time until the reservoir pool is emptied).This paper focuses on the description and hydraulics of overtopping breaches. The ultimate size of the breach must be described. This is the size expected when breach has stopped growing. The breach may stop growing because the entire dam has eroded or because the reservoir has drained and there is no more water available to erode the dam. The ultimate bottom elevation is the point at which erosion stops; usually either bedrock or the bottom of the reservoir pool. The breach size is described by a bottom width and side slopes. The conceptual development of a generalized trapezoidal overtopping breach is shown on Fig. 1.

It is necessary to define the circumstances of breach initiation (trigger mechanism) and how long it takes for the breach to progress to the ultimate size. The development time is the elapsed time from significant flow through the breach to the time at which ultimate size is reached. For overtopping failures the breach parameters should describe the initiation and progress of the hydraulic control (weir) that governs the release of water from storage.

Several options are available for identifying the breach initiation time. One option is to specify the duration that the pool elevation exceeds some threshold. This information may be the result of a geotechnical investigation. A second option is to specify a pool elevation; the breach begins to form as soon as that elevation is reached. The final option is a specific time during the simulation regardless of the pool elevation. This is useful for "sunny day" type failures that are not associated with a hydrologic event.

The breach shape develops in time from initiation to its ultimate configuration. The simplest development rate is linear; that is, the breach dimensions grow at a uniform rate. Options are available to simulate a breach that initially grows very quickly then slows down towards the end of the development time. Information for defining these growth rate parameters could be obtained from geotechnical information or from use of a process model such as NWS-BREACH (Fread, 1988a).

REVIEW OF GUIDANCE FOR BREACH PARAMETERS

Federal Agency Guidelines

Many federal agencies have published guidelines in the form of possible ranges of values for breach width, side slopes, and development time. Shown in Table 1 is a summary of guidance to date (USACE, 1980: USACE, 2007).

Table 1. Ranges of Possible Values for Breach Characteristics

Dam Type	Average Breach Width B_{ave}	Horizontal Component of Breach Side Slope (H) H:1V	Failure Time t_f (hrs)	Agency
Earthen/ Rockfill	(0.5 to 3.0) x HD	0 to 1.0	0.5 to 4.0	USACE (1980)
	(0.5 to 5.0) x HD	0 to 1.0	0.1 to 4.0[*]	USACE (2007)
	(1.0 to 5.0) x HD	0 to 1.0	0.1 to 1.0	FERC (1988)
	(2.0 to 5.0) x HD	0 to 1.0 (slightly larger)	0.1 to 1.0	NWS (Fread, 2006)
Concrete Gravity	Multiple Monoliths	Vertical	0.1 to 0.5	USACE (2007)
	Usually ≤ 0.5 L	Vertical	0.1 to 0.3	FERC
	Usually ≤ 0.5 L	Vertical	0.1 to 0.2	NWS
Concrete Arch	Entire Dam	Valley wall slope	≤ 0.1	USACE (1980)
	(0.8 x L) to L	0 to valley walls	≤0.1	USACE (2007)
	Entire Dam	0 to valley walls	≤ 0.1	FERC
	(0.8 x L) to L	0 to valley walls	≤ 0.1	NWS
Slag/ Refuse	(0.8 x L) to L	1.0 to 2.0	0.1 to 0.3	FERC
	(0.8 x L) to L		≤ 0.1	NWS

Where: HD = Height of the dam.
            L   = Length of the dam crest.
[*] Note: Dams that have very large volumes of water, and have long dam crest lengths, will continue to erode for long durations (i.e. as long as a significant amount of water is flowing through the breach), and may therefore have wider breach widths and longer times than what is shown.

Determining the size and growth rate for breaches is not a precise exercise. Therefore, simulation models such as HEC-RAS allow for the user to quickly evaluate the impacts of a range of parameters on the results. The Bureau of Reclamation (Wahl, 1988) offers an excellent literature review of this subject.

Regression Equations

The following regression equations have been used for several dam safety studies found in the literature and are being considered for inclusion in guidance for the Corps of Engineers Portfolio Risk Assessment study:

- Froehlich (1987,1995a,1995b)
- MacDonald and Langridge-Monopolis (MacDonald, 1984)
- Von Thun and Gillette (1990)

Froehlich utilized 63 earthen, zoned earthen, earthen with a core wall (i.e. clay), and rockfill data sets to develop a set of equations to estimate average breach width, side slopes, and failure time. In the application of these equations reported herein, the height of the breach is calculated by assuming that the breach goes from the top of the dam to the natural ground elevation at the centerline of the breach location.

MacDonald and Langridge-Monopolis (MacDonald, 1984):

MacDonald and Langridge-Monopolis utilized 42 data sets (predominantly earthfill, earthfill with a clay core, and rockfill) to develop a relationship for the "Breach Formation Factor." The Breach Formation Factor is a product of the volume of water released from the dam (V_{out}) and the height of water above the dam. They then related the breach formation factor to the volume of material eroded from the dam's embankment. The V_{out} parameter is not exactly known before performing the

breach analysis as it is the volume of water that passes through the breach (not including flow from gates, spillways, and overtopping of the dam away from the breach area). A good first estimate, however, is the volume of water in the reservoir at the time that the breach initiates. Once a set of parameters are estimated and a breach analysis is performed, a better estimate of the actual volume of water that passes through the breach can be made. Then the parameters can be recalculated using that volume. The recalculation of the volume makes the method iterative in these situations. The resulting ultimate breach dimensions are a function of the volume eroded and the embankment geometry. The MacDonald and Langridge-Monopolis paper states that the breach should be trapezoidal with side slopes of 0.5H:1V. The breach size is computed by assuming that the breach erodes vertically to the bottom of the dam and then erodes horizontally until the maximum amount of material has been eroded or the abutments of the dam have been reached. The base width of the breach can be computed from the dam geometry with the an equation given in (Washington, 1992). Note that the MacDonald and Langridge-Monopolis paper states that the equation for the breach formation time is an envelope of the data from earthfill dams. An envelope equation implies that the equation will tend to give high estimates of the actual breach time (for homogenous earthfill dams).

Von Thun and Gillette (Von Thun, 1990):

Von Thun and Gillette used 57 dams from both the Froehlich (1987) and MacDonald and Langridge-Monopolis (1984) papers to develop their methodology. The method suggests the use of breach side slopes of 1.0H:1.0V; except for dams with cohesive soils, where side slopes should be on the order of 0.5H:1V to 0.33H:1V. Von Thun and Gillette developed two different sets of equations for the breach development time depending upon the embankment material.

NWS-BREACH (Fread, 1988a):

The NWS-BREACH model is a "process" model in that it uses sediment mechanics and transport relationships to simulate the breach development. The model uses sediment transport equations to compute the rate of erosion and size of a breach given information regarding the soil characteristics of the dam material, the inflow hydrograph, etc. Enlargement of the breach over time is computed by sediment transport equations, sudden collapse due to excess hydrostatic pressure and width expansion by slope stability. Sediment transport equations are available for either cohesive or noncohesive materials.

Other process models such as SIMBA (Hanson, et al., 2005; Temple, et al., 2005) and HR-BREACH (Mohamed, 2002) are currently under development. At this time these models are undergoing testing with various field data and are not yet available for general use.

DAM BREACH FLOW SIMULATION USING HEC-RAS

The implementation of these breach parameters in the HEC-RAS modeling system is depicted on Fig. 2.
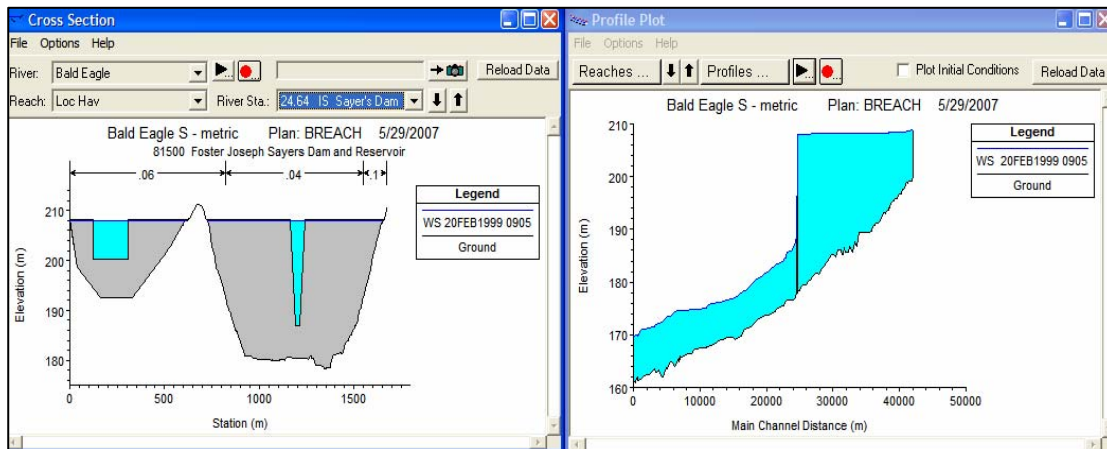
Figure 2. HEC-RAS Dam Breach Model

The graphical depiction of the breach size, location and progression associated with the computed upstream and downstream water surface profiles provides useful information for the analyst as well as the clients of the study. HEC-RAS uses dam breach parameters developed externally (using the techniques outlined above or any others deemed appropriate) to compute the temporal progression of a breach in an inline structure (dam). The flows through that structure are computed considering breach flow, overtopping flow, spillway discharges, gated flow, and submergence effects due to downstream backwater. Those several flow components are used as an internal boundary condition for unsteady flow modeling of the pool and the downstream reach. The pool may be analyzed using either simple level pool routing or as an unsteady flow reach using cross sections. Differences in breach outflow hydrographs due to different breach parameters will decrease as the floodwave is routed through the downstream reach.

SOME COMPARISONS

At this time, the breach parameter estimation methods described above have been applied to five situations. Two are hypothetical failures at actual projects. One of these has measured cross sections in the pool and the downstream reach so that the effects of in-pool and downstream routing can be examined. Three actual historic failures are also reproduced; one of which was a planned experiment. All of the cases discussed here are overtopping failures. In all cases the breach development was assumed to be linear in time. The hypothetical cases were assumed to start breaching when the overtopping was about 0.3 m; the reported beginning time of failure was used for the historic cases. Only the applications to the two historic failures are presented here due to space limitations; complete results can be found in (Gee and Brunner, 2007).

## APPLICATIONS TO SOME HISTORIC OVERTOPPING FAILURES

Oros Dam

Oros dam (Brazil) was under construction when it failed by overtopping in

March of 1960 (CEATI). The dam height was about 35.5m. It was composed of a clay core with sand and rock shoulders. The empirical methods of MacDonald, Froehlich and VonThun were applied to this structure along with the BREACH process model. The volume of water released was estimated to be $660*10^6$ m^3 (1). Table 2 summarizes the resulting breach parameters computed by these methods.

Table 2. Breach Parameters for Oros Dam

Oros	Parameter			
Method	W_b (m)	Side Slopes (h:v)	t_f (hrs)	Vol eroded (m^3)
MacDonald	900	0.5	3.7	$2.38*10^6$
Froehlich	305	1.4	4.8	
VonThun	132	0.33	1	
BREACH	284	0.6	7.3	
Reported	200	0	6.5 to 12	$0.87*10^6$

The breach outflow hydrographs computed using these parameters are shown on Fig. 3 with the estimated outflow hydrograph. The outflow hydrograph was deduced from the record of water level during the event (CEATI).
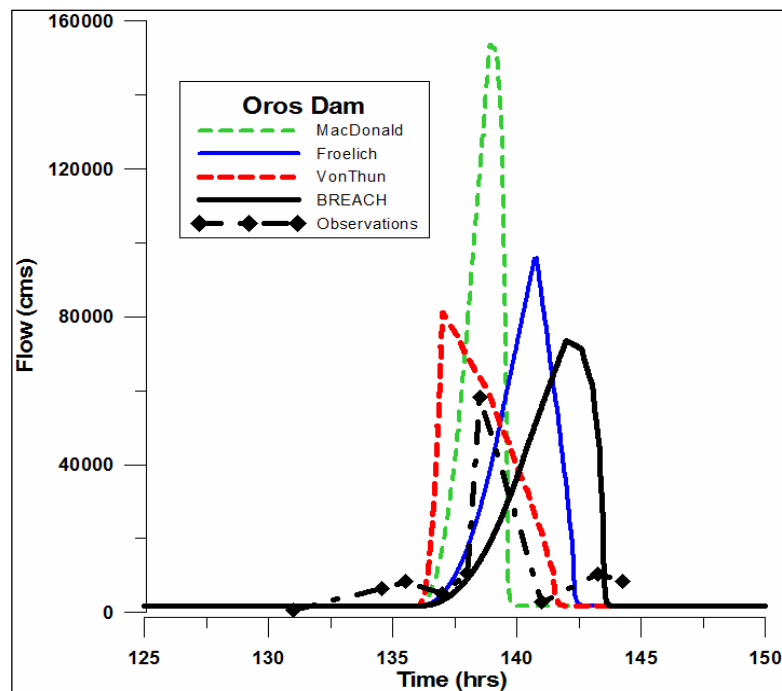
Figure 3. Breach Hydrographs for Oros Dam
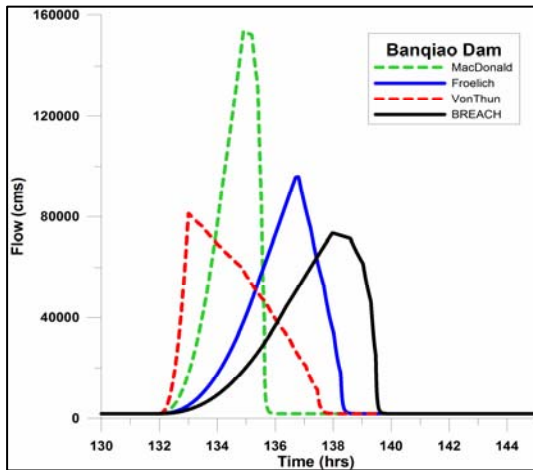
Banqiao Dam (China)

Banqiao Dam failed by overtopping from a large storm in 1975 (CEATI). The dam was constructed of a clay core containing shale. The upstream and downstream fill was homogeneous earth. It can be assumed that, due to construction methods (primarily non-mechanized), that the core was poorly compacted. The dam

was about 24.5 meters high with a crest elevation at 116.34m. Crest width was 6m and length 2020m. The upstream slope was 3H:1V and downstream 2.5H:1V. The design capacity for the spillway and outlet works was 1742 m^3/sec; the estimated peak inflow was about 13,000 m^3/sec when breaching occurred. The estimated breach parameters are shown in Table 3.

The breach outflow hydrographs computed using these parameters are shown on Fig. 4. Field observations for this event consist of the pool elevation time history. These observations can be compared with the pool drawdown computed using HEC-RAS with the estimated breach parameters as shown on Fig. 5.

Table 3. Breach Parameters for Banqiao Dam

Banqiao	Parameter			
Method	W_b (m)	Side Slopes (h:v)	t_f (hrs)	Vol eroded (m^3)
MacDonald	1037	0.5	3.4	$1.85*10^6$
Froehlich	281	1.4	7	
VonThun	108	0.33	0.7	
BREACH	641	0.6	3.6	
Reported	210	0	1.5	$0.6*10^6$

Figure 4. Breach Hydrographs for Banqiao Dam
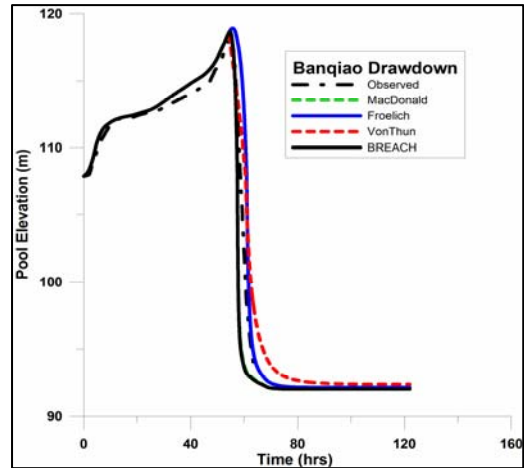
Figure 5. Pool Drawdown for Banqiao Dam

CONCLUSIONS AND OBSERVATIONS

Several techniques are available for estimating the breach parameters resulting from dam overtopping and subsequent failure. These techniques are predominately empirical, based on fitting relationships between key parameters such as water depth behind the dam and historic observations. One process model, NWS-BREACH, was also applied for comparison.

Estimation of dam breach parameters is a necessary first step in performing the analysis of the downstream consequences of possible dam failures. These parameters are used to compute breach outflow hydrographs using estimated inflow hydrographs, reservoir elevation-capacity data, and spillway and gate hydraulic capacities. Techniques are being developed to interpret and utilize the breach parameters estimated by application of these methods in an unsteady flow model; HEC-RAS. The methods predict a wide range of breach parameters and therefore, a large difference in outflow hydrographs. The MacDonald method routinely produced the largest peak outflows. The only comparison to an estimated historic outflow hydrograph (Oros) showed that all of the methods produced flows larger than those observed. For the case in which the pool drawdown data were available, all of the methods, when used in the HEC-RAS simulation model, produced comparable results.

The methods tested suggest use of flatter breach side slopes than are typically observed. The bases for development of the empirical techniques must be kept in mind. The breach configuration used in developing the regression equations was typically the ultimate shape that was observed at the after the event. What is needed for computing outflow hydrographs is the progression of the hydraulic control; be it a weir flow in the case of overtopping or an orifice flow in the case of piping. The hydraulic computations done in HEC-RAS assume that the hydraulic control progresses based on a failure time estimated from the method applied. Downstream submergence of the control is possible and is included in the outflow computation.

Process models are currently being developed and tested (Wahl, et al., 2008). The expected advantage of this type of model will be the ability to relate breach parameters to the materials and construction of the structure of interest. Tracking of the progression of the hydraulic control during breaching should be improved as well.

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